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The Astrolabe Craftsmen of Lahore and Early Brass Metallurgy

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Summary

A study of the metallurgy and manufacturing techniques of a group of eight astrolabes (seven from Lahore, one attributed to India) using non-destructive methods has produced the earliest evidence for systematic use of high-zinc ($\alpha+\beta$) brass. To produce this alloy, the brass industry supplying the Lahore instrument makers must have co-melted metallic copper and zinc. This brass-making technology was previously believed to have been developed on an industrial scale in the nineteenth century in Europe. This work hypothesizes that this technology was used in Lahore on an industrial scale as early as ad 1601. In addition, this work hypothesizes that the $\alpha+\beta$ brass alloy was used specifically for its ease in manufacturing the thin sheet brass required for astrolabe-component manufacture.

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1. Introduction

The planispheric astrolabe (hereafter astrolabe) represents the ingenious application of spherical geometry to map one's location on Earth relative to the stars and sun on the celestial sphere. Often considered the first modern scientific instrument, the astrolabe was used to determine the time of day or night as well as other astronomical computations. It was the most important tool to the pre-telescopic astronomer. There have been many studies of astrolabes in the past, but these have tended to focus on individual makers, locations, or unique instruments. Relatively few studies exist of astrolabe manufacturing techniques or the metallurgy of astrolabes themselves. Gordon has published two studies in which direct examination of the brass microstructure of two German astrolabes by Hartmann was used to determine the alloy composition, metal working and thermal annealing history, and the use of division of labour in the production workshop.[1] However, traditional metallography is a destructive process, and it is understandable why curators and collectors are hesitant to allow sampling or *in situ* metallographic study of their instruments.

One might ask why it is important to study the metallurgy and forming processes used in astrolabe manufacture. The astrolabe was widely used throughout both the Eastern and Western world, and remained relatively unchanged in its physical appearance throughout its centuries of use. Therefore, it represents a common artefact of the state of the art in both Eastern and Western lands. Regardless of time period or location of manufacture, astrolabes were typically produced of brass. By studying the metallurgy and techniques used to produce astrolabes, one can learn of the technology employed by the non-ferrous metalworker of the day.

The emerging analytical technique of high-energy synchrotron X-ray analysis is a tool that can overcome the disadvantages of traditional metallography while providing all of the required data to determine the sample's chemistry and forming processes. The synchrotron provides the user with a source of high-flux, high-energy X-rays (up to 100 keV) with which to perform experiments.[2] To produce these X-rays at the Advanced Photon Source synchrotron of Argonne National Laboratory, the synchrotron accelerates electrons to relativistic speeds around a 1.1 km storage ring. X-rays are generated and channelled to the experimental station when the electrons in the storage ring pass through deflecting magnets. Some of the advantages of synchrotron X-rays over a laboratory X-ray tube source are both the tunable energy and very high flux, which allows long-range penetration of highly X-ray absorbent samples.

Stephenson et al. have used synchrotron-based X-ray techniques to analyse two astrolabes attributed to Ioannes Bos, illustrating the possibility of determining the metal forming processes used in astrolabe manufacture as well as for authentication of the astrolabes.[3] This report expands on these techniques to examine a collection of seven astrolabes manufactured in seventeenth-century Lahore and one astrolabe

[1] R.B. Gordon, 'Sixteenth-Century Metalworking Technology Use in the Manufacture of Two German Astrolabes', *Annals of Science*, 44 (1987), 71–84.
R.B. Gordon, 'Metallography of Brass in a Sixteenth Century Astrolabe'. *Historical Metallurgy*, 20 (1986), 93–96.

[2] For a more thorough introduction and explanation of synchrotrons, please visit the home page of the Advanced Photon Source synchrotron at www.aps.anl.gov.

[3] G.B. Stephenson, B. Stephenson, and D.R. Haeffner, 'Investigations of Astrolabe Metallurgy Using Synchrotron Radiation', *MRS Bulletin*, 26 (2001), 19–23.

Figure 1. Astrolabe A-70.

attributed to eighteenth-century India. Figure 1 illustrates astrolabe A-70 constructed by Diyā al-Dīn Muhammad of Lahore and included in this study. These eight astrolabes represent a subset of a larger study of 40 astrolabes of the Adler Planetarium collection representing all major astrolabe production centres and time periods of astrolabe production and use. Metallurgical study of the products from Lahore promised to reveal much about the techniques available to the most advanced metal craftsmen of Moghul India. As it turned out, this investigation has placed the Lahore brass industry and astrolabe craftsmen at the forefront of brass technology in the seventeenth century. Astrolabes are fashioned primarily from copper alloys, brass in particular, which has either been hammered into sheets or cast into thicker shapes. We shall find that the need to hammer out sheet brass (such as that required for astrolabe plates) imposed certain constraints on which metal alloys could be efficiently used, constraints that the Lahore brass-making industry recognized and satisfied by developing the most advanced brass technology in the world.

2. Lahore school of instrument makers

The eight instruments examined in the present study were fabricated, in the sixteenth and seventeenth centuries (by the European calendar), in or around Lahore, a city in present-day Pakistan. At that time, Lahore was already an ancient

Table 1. Astrolabes examined in this study.

Adler ID no.	Maker	Date (ad)	Location
A-70	Diyā' al-Dīn Muhammad	1647/8	Lahore
A-78	Diyā' al-Dīn Muhammad	1662/3	Lahore
A-79	Isa ibn Allāhdād	1604/5	Lahore
A-81	Diyā' al-Dīn Muhammad	1660/1	Lahore
A-86	Diyā' al-Dīn Muhammad	1637/8	Lahore
L-100	Unknown	Seventeenth century	Lahore (attributed)
N-69	Isa ibn Allāhdād	1601	Lahore
N-68	Unknown	Eighteenth century	India (attributed)

cultural centre in Moghul India, and home to a skilled and prolific family of instrument makers.[4]

The patriarch of this family was named Allāhdād, later known as Allāhdād al Humāyūnī to assert that he had made astrolabes for the Moghul emperor Humāyūn, who reigned in Delhi from ad 1530 to 1556. None of Allāhdād's handful of surviving instruments was included in this study, but his son 'Īsa ibn Allāhdād made and signed two astrolabes that were among those studied. Four additional astrolabes in the study were signed by Diyā al-Dīn Muhammad, grandson of 'Īsa, and dated variously between ad 1637 and 1663. An unsigned astrolabe, ingeniously designed for use in both northern and southern latitudes, has been attributed on stylistic grounds to the seventeenth-century Lahore workshop and was included.[5] Another unsigned instrument, more loosely attributed to eighteenth-century India, was also studied. These eight instruments, seven from the seventeenth century and one from the eighteenth, are the subject of the analysis reported here. See Table 1.[6]

Lahore astrolabes are of a class termed 'Indo-Persian' because their inscriptions are in Arabic/Persian characters rather than in Sanskrit. They were typically characterized by a high, frequently pierced, and intricately shaped throne or *kursi* (the part to which the suspension ring was attached), indicating a sophisticated metalworking technology. The rete is often of a 'foliate' design, with leaf-shaped star pointers. Engravings on the back and in the cavity tend to be elaborate and highly decorative, as remarked by Gunther, Sarma, and others.[7]

It is of some interest that the same family of Lahore metalworkers specialized also in making celestial globes, a demanding craft because of the difficulty of shaping metal into the form of a hollow sphere. Diyā al-Dīn Muhammad, in particular, was a prolific maker of both astrolabes and globes. Three celestial globes from Lahore, and a filigree celestial sphere by Diyā, are in the Adler collection. Although these were not included in the present study (their shape was unsuited to the sample mounting methods used here for two-dimensional astrolabe components), metallurgical

[4] On the Lahore instrument makers see S.R. Sarma, 'The Lahore family of astrolabists and their ouvrage,' *Studies in History of Medicine and Science* 13 (1994), 203–24; E. Savage-Smith, *Islamicate Celestial Globes* (Washington, 1985), 34–44 *et passim*.

[5] A.J. Turner, *The Time Museum Volume 1, Time Measuring Instruments: Part 1 Astrolabes and Astrolabe Related Instruments* (Rockford, IL, 1985), 74–83.

[6] Lahore workshops continued to produce astrolabes into the nineteenth century. None of these later Lahore astrolabes, however, are in the Adler collection.

[7] R.T. Gunther, *The Astrolabes of the World*, 2 vols (Oxford, 1932), I.
S.R. Sarma, 205–24.

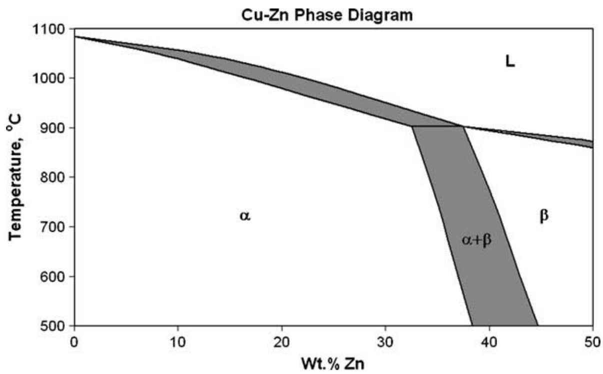

Figure 2. Cu/Zn phase diagram illustrating the metallurgical phases present for a range of temperatures and alloy compositions.

analysis elsewhere has revealed that such 'Islamicate celestial globes' were made from an alloy of primarily copper, with significant amounts of lead (12–30%), and smaller quantities of zinc, tin, and trace impurities.[8] Lead was presumably added to make the alloy more suitable for casting; we shall find that the same was done in alloys intended for cast components of astrolabes.[9]

3. Introduction to brass metallurgy and cementation brass production

Nearly all astrolabes in existence are made of brass, regardless of location and time of production. The manufacture of brass in antiquity poses quite an interesting problem because metallic zinc was very rare—there is no evidence for intentional zinc production on a practical scale in Europe until the mid-nineteenth century, while zinc production in the East seems limited to Zawar, India (starting in the thirteenth century)[10] and Western China (starting in the sixteenth century).[11] Despite the evidence for zinc production in these regions, there is a curious lack of physical evidence for brass production via direct alloying. To understand how the ancients manufactured brass and the significance of this work's results, we must first acquaint ourselves with the metallurgy of the Cu/Zn alloy system.

3.1. *Cu/Zn phase diagram*

Figure 2 illustrates the binary phase diagram for the Cu/Zn system of brass (for alloys with compositions of 0–50 wt.% Zn). The diagram provides a 'map' for which metallurgical phases will be present for any given temperature and composition

[8] E. Savage-Smith, p. 93.

[9] On these globes, see Savage-Smith (1984). Although it is perfectly possible to fashion metal globes by combining two individually shaped hemispheres, the Lahore craftsmen preferred to make so-called 'seamless' globes using the demanding lost-wax (*cire perdue*) method, well described by Savage-Smith, which yields a more truly spherical shape at the cost of a great deal of tedious labour.

[10] P.T. Craddock, I.C. Freestone, L.K. Gurjar, A.P. Middleton, and L. Willies, 'Zinc in India', in *2000 Years of Zinc and Brass Revised Edition*, edited by P.T. Craddock, (London, 1998), 27–72.

[11] W. Zhou, 'Chinese Traditional Zinc Smelting Technology and the History of Zinc Production in China'. *Bulletin of the Metals Museum*, 25 (1996), 36–47.

represented on the x- and y-axes for the Cu/Zn binary system.[12] The different metallurgical phase regions on the phase diagram indicate the crystal structure and composition, i.e. the arrangement of the copper and zinc atoms of the alloy on an atomic level. Each metallurgical phase has different physical properties, and the metallurgical phases present in a sample and their distribution define the mechanical properties of that alloy on the macroscopic scale. A methodology to determine the crystal structure and composition of an alloy combined with a knowledge of the phase diagram for that binary system can then lead to a better understanding of the alloy's physical properties and fabrication technology.

The phase diagram of Figure 2 consists of regions where one or two metallurgical phases are thermodynamically stable for the given temperature and composition. The single-phase regions are labelled for the stable phase (α for alpha brass, β for beta brass, L for liquid), while the two-phase regions are shaded. The phases present in the two-phase regions are defined by the single-phase regions on either side – $\alpha+L$ for the region between the α and L single-phase regions, $\alpha+\beta$ for the region between the α and β single-phase regions, etc. The left and right edges of the diagram in Figure 2 represent either pure copper or 50 wt.% copper and 50 wt.% zinc, with continually varying binary alloy compositions in between. Pure copper is represented at the far left edge of the diagram; we see that it does not melt until 1085°C. As the zinc composition is increased (represented by moving right along the x-axis), the melting temperature of the alloy decreases, as shown by the boundary line between the liquid phase field (labelled 'L') and the grey phase fields for $L+\alpha$ and $L+\beta$. There are three solid phase fields that concern us, the α (0–38 wt.%), $\alpha+\beta$ (38–45 wt.%), and β (45–50 wt.%) phase fields.[13] The α and β phases will not be discussed in depth here; it is only important to realize that their presence is tied to specific alloy compositions. It follows that evidence of α only, $\alpha+\beta$, or β only gives the examiner an immediate clue about the composition of the sample.

3.2. *Brass production by the cementation process*

The first brass to appear in large amounts in Europe was formed in Roman times, and therefore we know that the Romans had a method for the mass production of brass.[14] It is commonly accepted in the literature that brass produced on an industrial level before the eighteenth century was limited to 28–32 wt% Zn, in the α region of Figure 2.[15] This compositional limit was a result of the brass-manufacturing process, developed by the Romans, commonly referred to as the cementation (or calamine) process. The cementation process allowed the Romans (and later the rest of the world) to produce brass without requiring metallic zinc.[16] The process, first recorded

[12] For a complete description of phase diagrams, please see *ASM Handbook Volume 3: Alloy Phase Diagrams*, edited by H. Baker (Materials Park, OH, 1992), Section 2, 182.

[13] These composition ranges are approximate, since the phase boundary changes with temperature as seen in figure 2. For an in-depth discussion of the temperature dependence on the phase boundaries of the α and $\alpha+\beta$ phase fields, please see pp. 146, 164–65 of Brian Dale Newbury, 'A non-destructive synchrotron X-ray study of the metallurgy and manufacturing processes of Eastern and Western astrolabes in the Adler Planetarium collection' (doctoral dissertation, Lehigh University, 2005).

[14] J. Bayley, 'Roman Brass-Making in Britain', *Historical Metallurgy*, 18 (1984), 42–43.A.M. Pollard and C. Heron, *Archaeological Chemistry* (Cambridge, 1996), 196–238.

[15] K. Haedecke, 'Equilibria in the Production of Brass by the Calamine Process', *Erzmetall*, 26 (1973), 229. P.T. Craddock, *Early Metal Mining and Production* (Edinburgh, 1995), 292–302. Joseph B. Lambert, *Traces of the Past: Unraveling the Secrets of Archaeology Through Chemistry* (Reading, MA, 1997), 192–93. R.F. Tylecote, *A History of Metallurgy* (London, 1976), 96.

[16] J. Bayley, 42–43.

in Europe by Theophilus, was widely used around the world until the nineteenth century.[17] Excellent reviews of the cementation process can be found for Islamic production[18] and for European production.[19]

Aside from minor differences in zinc ores and heating schedules discussed in the previously mentioned papers, both Islamic and European cementation brass production rely on the same principal steps. Metallic copper is placed in a deep crucible containing charcoal and zinc oxide/ore. This crucible (which can be open, or lidded to improve the efficiency of the process) is then heated to 1000–1100°C. At this temperature, the charcoal reduces the zinc oxide to zinc gas and carbon dioxide according to the following chemical reaction:

$$2\mathrm{ZnO} + \mathrm{C} \rightarrow 2\mathrm{Zn(gas)} + \mathrm{CO_2}. \tag{1}$$

The gaseous zinc then diffuses into the copper to form brass.

The temperature at which the cementation brass is manufactured has a large effect on the zinc composition of the alloy. In modern cementation-process-reproduction experiments, Haedecke found that a maximum of 32 wt.% zinc could be absorbed by the copper, indicating that this was determined by a balance of zinc volatization out of the newly formed brass and diffusion of zinc into the brass.[20] Archaeological and historic brasses manufactured in European or Islamic workshops should therefore follow this composition maximum. Referring to the phase diagram of Figure 2, this composition limit indicates that all cementation brasses should be α brass only. This result has been supported with few exceptions in the literature, with published chemical compositions of historical brasses holding to this limit.[21]

4. Experimental procedures

While they are not the main focus of this work, it is important to have a common understanding of the experimental procedures employed in this study. A more in-depth discussion of the techniques as they pertain to a wider study of astrolabes and archaeological materials can be found in Newbury.[22] For the current study, a subset of eight astrolabes produced around Lahore (listed in Table 1) from a larger study of 40 Eastern and Western astrolabes of the Adler Planetarium was examined to determine the alloys and manufacturing processes involved in their production. The astrolabes were examined via three non-destructive synchrotron-based X-ray techniques: (1) transmission X-ray diffraction (XRD), (2) X-ray fluorescence (XRF), and (3) X-ray radiography. The mater of astrolabe N-68 can be seen mounted for synchrotron analysis in Figure 3. From the XRD results, it is possible to determine the average composition of the brass alloy, the metallurgical phases present in the alloy's microstructure, and the forming history used to shape the

[17] Joan Day, 'Brass and Zinc in Europe from the Middle Ages Until the Mid-Nineteenth Century', in *2000 Years of Zinc and Brass Revised Edition*, edited by P.T. Craddock, (London, 1998), 147.

[18] P.T. Craddock, S.C. La Niece, and D. Hook, 'Brass in the Medieval Islamic World', in *2000 Years of Zinc and Brass Revised Edition*, edited by P.T. Craddock (London, 1998), 73–114.

[19] M. Martinon-Torres and T. Rehren, 'Agricola and Zwickau: Theory and Practice of Renaissance Brass Production in SE Germany', *Historical Metallurgy*, 36 (2002), 95–111.

[20] K. Haedecke, 229–33.

[21] A.M. Pollard and C. Heron, 196–234.
P.T. Craddock, S.C. La Niece, and D. Hook, 73–114.

[22] Brian Dale Newbury, 102–45.

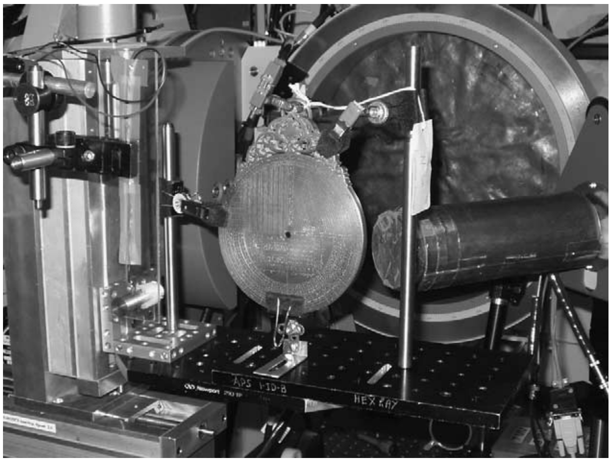

Figure 3. Astrolabe N-68's mater mounted for examination at the APS synchrotron.

astrolabe component. XRF allows near-surface measurement of the astrolabe component composition, an important test to check the uniformity of the alloy. The radiography results allow accurate thickness measurements and thickness traces to be plotted, which are useful to determine the forming processes used.

5. Results and discussion

When examining the data produced by the XRD experiments, it was found that the astrolabe production centre of Lahore was using a remarkably different brass alloy than was commonly used for brass work of any manner throughout the rest of the world. Preliminary results from this study were published previously,[23] but a more complete picture of the alloy's use and purpose has now been determined. From the preceding section, we expect that brass produced during the time period of the Lahore astrolabes' production should be limited to approximately 32 wt.% zinc. Figure 2 indicates that only α brass would be present in the microstructures. For many components, this is the case as seen for astrolabe A-81's alidade illustrated in Figure 4A and 4B. However, by synchrotron XRD, it was found that all of the astrolabes contained components with both α and β' brass phases present in the microstructure, as shown in Figure 4C and 4D.[24] From the phase diagram in Figure 2, it can be seen that a brass with both α and β phases present must be between approximately 33 and 45 wt.% zinc. Since this brass alloy exceeds the composition of brasses produced by the cementation process, the Lahore brass must have been produced by another technique.

The astrolabes and astrolabe components studied are listed in Table 2; the components named in boldface show evidence via synchrotron XRD for the $\alpha+\beta$

[23] B. Newbury, B. Stephenson, J. Almer, M. Notis, G.S. Cargill, III, G.B. Stephenson, and D. Haeffner, 'Synchrotron Applications in Archaeometallurgy: Analysis of High Zinc Brass Astrolabes', *Powder Diffraction*, 19 (2004), 12–15.

[24] The difference between ? and ?′ is immaterial to the scope of this work, but for a further discussion see Brian Dale Newbury, 146–255.

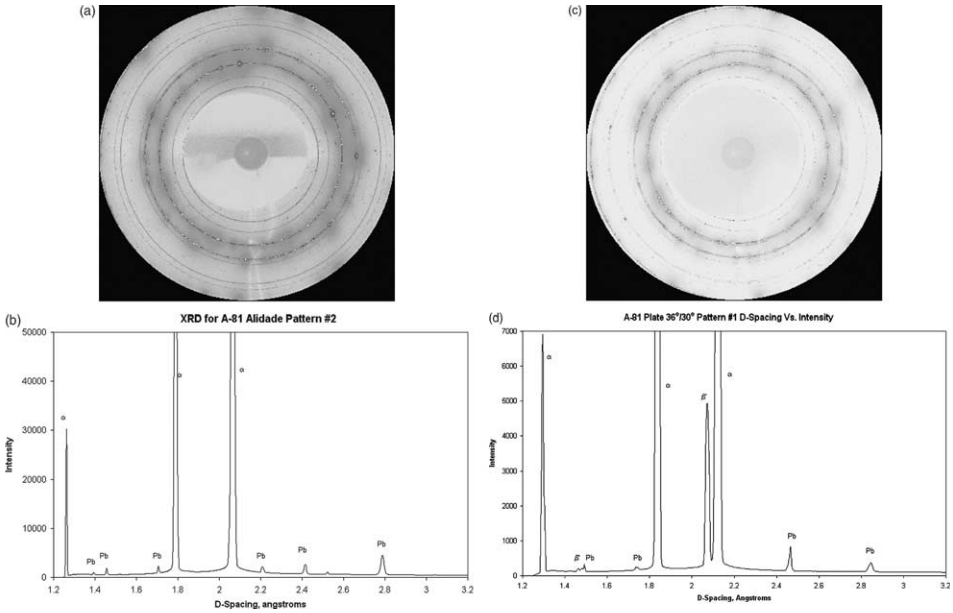

Figure 4. (A) A raw and (B) analysed synchrotron transmission diffraction pattern illustrating α brass and metallic lead phases present in the microstructure of astrolabe A-81's alidade. (C) Raw and (D) analysed synchrotron transmission diffraction patterns illustrating metallic lead as well as α and β′ brass phases present in astrolabe A-81 plate 36°/30°.

brass alloy, while the components named in normal text exhibit α brass evidence only. When examining the list of $\alpha + \beta$ brass components, it can be seen that with few exceptions, they are components made from sheet brass (plates and retes). The question arises: why would astrolabe retes and plates from Lahore use a different brass alloy than all other brass foundries and metal workshops throughout Islamic and European lands?

Figure 5 illustrates a radiography trace across the 30°/36° plate of astrolabe N-68. The large-scale (tens of millimetres) random thickness variation is an indication of sheet forming via a hand hammering process, a result of the variance of force used in each hammer blow.[25] The much sharper small-scale thickness decreases (on the order of 1 mm wide) indicate the location of engraving features on either surface of the plate. Before modern industrial practice, sheet brass was produced by casting a plate approximately 8–10 mm thick followed by hand-hammering it to the final thickness desired.[26] However, to produce a 1-mm-thick sheet from a 30 wt.% Zn α brass alloy, such as that produced by the cementation process, a large number of working and annealing cycles would be required. Assuming an optimal case, it is possible to obtain a forty per cent reduction in thickness before annealing must be performed.[27] This

[25] J. Lang, 'Chapter 2 Metals', in *Radiography of Cultural Material*, edited by J. Lang and A. Middleton (Oxford, 1997), 41.

[26] Sandra K. Zacharias, 'Brass Making in Medieval Western Europe', in *All That Glitters: Readings in Historical Metallurgy*, edited by Michael L. Wayman (Montreal, 1989), 37.
A. Sisco and C.S. Smith, *Lazarus Ercker's Treatise on Ores and Assaying* (Chicago, 1951), 258.

[27] J.H. Mendenhall, *Understanding Copper Alloys* (New York, 1977), 42.

Table 2. All astrolabes studied with evidence for $\alpha+\beta$ brass usage[a].

Accession no.	Components present[b]	Location
A-70	Vane, **Mater**, Pin, **Rete**, Ring, **Shackle**, **Plate 1**, **Plate 2**, **Plate 3**, **Plate 4**	Lahore
A-81	Alidade, Wedge, Mater, Pin, **Rete**, **Plate 1**, **Plate 2**, **Plate 3**, **Plate 4**, **Plate 5**, Washer	Lahore
A-86	**Alidade, Mater**, Pin, Rete, **Plate 1**, **Plate 2**, **Plate 3**, **Plate 4**	Lahore
A-78	Alidade, Wedge, **Mater**, Pin, **Rete**, **Plate 1**, **Plate 2**, **Plate 3**, **Plate 4**, **Plate 5**	Lahore
L-100	**Wedge**, Mater, **Pin**, Rete North, **Rete South**, **Rule**, Plate 1, **Plate 2**, **Plate 3**, **Plate 4**, **Plate 5**, **Plate 6**, Plate 7	Lahore
N-69	**Alidade**, **Mater**, **Rete**, Screw, **Plate 1**, **Plate 2**, **Plate 3**, **Plate 4**, **Plate 5**	Lahore
A-79	Alidade, Wedge, Mater, Pin, Rete, **Plate 1**, **Plate 2**, **Plate 3**, **Plate 4**, **Plate 5**, **Plate 6**, **Plate 7**, **Plate 8**	Lahore
N-68	Alidade, Washer, Wedge, Mater, Pin, Rete, Plate 1, **Plate 2**, **Plate 3**, Plate 4, Plate 5, Plate 6, Plate 7	India

Notes:
[a]Bold type indicates component with $\alpha+\beta$ brass evidence by XRD.
[b]The plates are listed by number in this work for easy identification. For more specific details on the plates' markings, please consult Dr. Bruce Stephenson at the Adler Planetarium address.

annealing step is required to relieve the internal stresses induced into the metal during the deformation process — further deformation without annealing would cause the metal to crack. To produce a 1-mm-thick brass sheet for an astrolabe plate (a common thickness for Eastern astrolabes which have up to eight plates in one astrolabe), a mechanical working schedule would be similar to this:

- hammer 10-mm plate to 6 mm, anneal;
- hammer 6-mm thick brass plate to 3.6 mm, anneal;
- hammer 3.6-mm thick brass plate to 2.2 mm, anneal;
- hammer 2.2-mm thick brass plate to 1.3 mm, anneal;
- hammer 1.3-mm thick brass plate to the desired thickness.

Therefore, a minimum of four annealing steps (and most likely five to seven) are required to produce the brass sheet from which an astrolabe plate can be manufactured.

If the Zn content of the brass is increased to bring it into the two-phase $\alpha+\beta$ region, the alloy lends itself to being hot-worked.[28] In hot working, the deformation and recrystallization of the metal occur simultaneously, eliminating the need for annealing.[29] It follows that a 10-mm plate of $\alpha+\beta$ brass could be heated to the desired hot working temperature and hammered to the desired thickness in one step. There is evidence in the Islamic literature of India that this was empirically known in the late sixteenth century as published in the *Ā'īn-I-'Akbarī* of Abū 'l-Fadl.[30] In addition, Allen mentions that the modern forging brass alloy (60 wt.% Cu, 38 wt.% Zn, 2 wt.% Pb) possesses the best hot working properties when heated above 500°C.[31]

[28] D.K. Allen, *Metallurgy Theory and Practice* (Chicago, 1969), 430–40.
[29] J.H. Mendenhall, p. 12.
[30] A.Y. Al-Hassan and D.R. Hill. *Islamic Technology: an Illustrated History* (Cambridge, 1986), 249–50.
[31] D.K. Allen, p. 438.

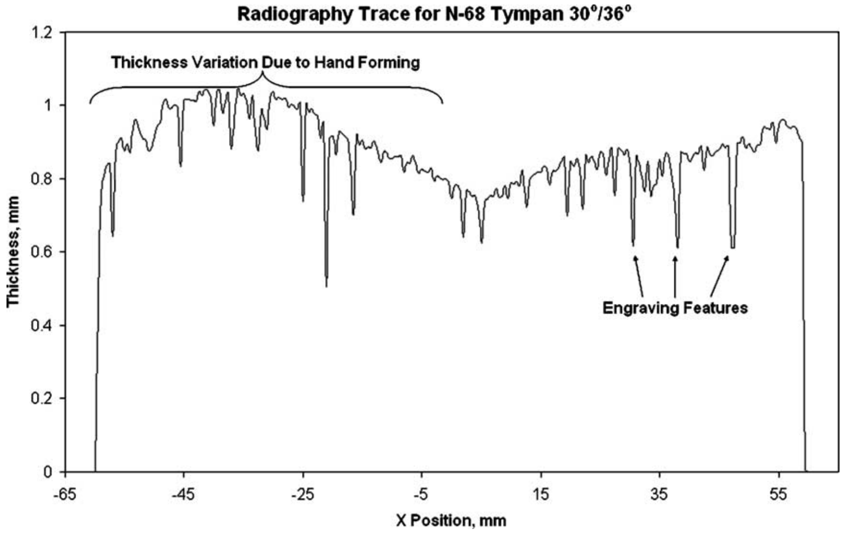

Figure 5. Radiography trace illustrating plate thickness vs. position for astrolabe N-68 plate 30°/36°.

This happens to correspond with the 1–2 wt.% Pb found in the majority of high-Zn plates and retes manufactured from hand-forged sheet. Figure 6 overlays the temperature and composition ranges for various deformation regimes and heat treatments on top of a Cu–Zn phase diagram to illustrate how these characteristics relate to the phases present in the microstructure. As the zinc composition is increased from the α to the $\alpha+\beta$ phase fields, the hot deformation properties increase, and the hot deformation temperature decreases. This temperature decrease makes it easier for the metalworker to produce the metal sheet under optimal conditions.

The question remains as to how this dual phase brass was produced. Experiments have shown that the 32 wt% Zn composition limit is valid for commercial-scale brass production via cementation.[32] The only technique capable of producing the dual-phase alloy is direct co-melting of metallic copper and zinc; hence, the metalworkers and brass founders of Lahore must have had access to metallic zinc. It is most likely that this zinc originated in the Zawar region of Rajasthan in Northwestern India, south of Lahore. Craddock has shown well-documented evidence for metallic zinc production on a large scale in Zawar since at least the thirteenth century ad.[33] Due to the large amounts of zinc produced, 30,000 tons over 400 years, it was hypothesized that this zinc was used for brass production in addition to the production of medical salves.[34] However, the lack of a significant body of conclusive physical evidence had left this as a hypothesis. We believe that the data published in this study constitute the first large body of evidence for systematic use of metallic zinc in brass production.

[32] B. Newbury, M. Notis, and D. Newbury, 'Revisiting the zinc composition limit of the cementation process of brass manufacture', *Historical Metallurgy*, in press.
[33] P.T. Craddock, I.C. Freestone, L.K. Gurjar, A.P. Middleton, and L. Willies, 27–72.
[34] A.K. Biswas, *Minerals and Metals in Pre-Modern India* (New Delhi, 2001), 141–85.

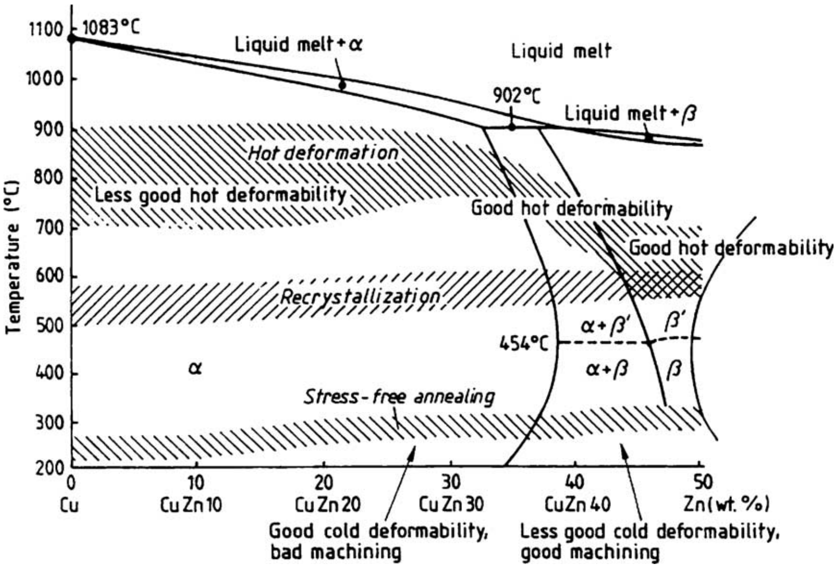

Figure 6. Copper-rich region of the Cu/Zn phase diagram with heat-treating and deformation properties overlaid. This figure is based on work published by the German Metalforming Society. *Kupfer-Zink-Legierungen*. Deutsches Kupfer-Institut (Berlin, 1991), Informationsdruck I.5.

It is the presence of the β phase which gives proof of direct co-melting copper and zinc metals. Of course, it is possible to produce a brass of lower composition via co-melting, and it would be very hard if not impossible to definitively determine if the brass was made by co-melting or cementation by analytical methods alone. However, from the phase diagram in Figure 2, it is shown that the presence of β requires a higher zinc composition than can be produced by a cementation brass, proving the use of direct co-melting. The fact that all Lahore and Indian astrolabes examined showed evidence for the use of the dual-phase brass indicates that the technology and knowledge to exploit the hot working alloy were well known by ad 1601, the production date of the earliest astrolabe in this study.

6. Conclusions

All seven astrolabes examined from Lahore and one astrolabe attributed to India contained components constructed of an advanced dual-phase $\alpha + \beta$ brass alloy. This alloy was most likely chosen specifically for its capability for hot deformation, which allows a thin brass sheet to be produced much faster and easier than with the standard α brass alloy in use elsewhere in the world. The use of this dual-phase brass alloy indicates a fundamental shift in the brass production industry in and around Lahore, a shift from the cementation process of brass production to that of co-melting. This shift required the technology to produce metallic zinc, which has been documented to exist in the nearby Zawar region of north-western India. The evidence for dual-phase brasses presented in this work is believed to be the first documented evidence for large-scale brass production by co-melting, as well as the

earliest evidence for a designed hot-working alloy. Given Lahore's reputation as a metalworking centre for Mughal India, it would be very interesting to examine other thin-sheet brassware (such as serving trays) produced in Lahore to determine how widely the $\alpha + \beta$ alloy was used. These technologies were well established by ad 1601, the date of the earliest astrolabe included in this study, and approximately 250 years before similar technology was available for practical use in the West. A further study of earlier sheet brass artefacts (both astrolabes and other forms) should be performed to elucidate the date of development of this advanced brass alloy and, by implication, the beginnings of the modern brass industry.

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